EVALUATION OF RESEARCH REACTOR FUEL RELIABILITY IN SUPPORT OF REGULATORY REQUIREMENTS

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ABSTRACT

This standards, codes and practices survey is devoted to the problem of reliability of R&D especially research reactor fuel (RRF) performance-related processes.
Regulatory R&D evaluations were based on one standard and just few of them provide correlation to other relative standards whereas synthetic process approach reflects actual status of particular R&D practices. Fuel performance regulatory parameters are based on quality standards. A reliability process-based method similar to PSA/FMEA is proposed to evaluate RRF performance- related parameters in terms of reactor safety.

1. Introduction

Industrial regulations have historical links to quality assurance/quality control (QA/QC) principles: originally, QA/QC principles were brought into nuclear safety regulations through reactor pressure boundary component (RPBC) life-cycle applications. Relationships between QC specifications for RPBCs and their operational reliability are usually expressed in the form of stress analysis equations and related direct destructive and non-destructive (ND) tests. In other words, RPBCs are a subject of deterministic design and an operational approach.

The purpose of and performance model for nuclear fuel are different from those for RPBCs: fuel is a temporary, burnable type of equipment. Thus, some essential direct industrial tests are not applicable to fuel; e.g., tests that are similar to the in-service ND control of reactor pressure vessel weld defects. In effect, fuel-related QA principles are based on a probabilistic statistical approach, which would guarantee the reliability of basic operational parameters for fuel, limited to the relatively short operational time of the fuel life cycle.

Therefore, unlike major RPBCs, nuclear fuel is usually not a subject of any specific regulatory surveillance program that is (historically) based on deterministic principles. Taking into consideration that fuel manufacturing companies are quite often owned by nuclear power generating station (NPGS) operators, we could suggest fuel manufacturing, purchasing and operational performance QA are all internal processes within the same company. Research and development (R&D, e.g., post-irradiation examination) is an essential part of fuel operational performance assessment. This type of R&D is usually provided by the fuel design organization on a permanent basis, and concludes the continual QA improvement loop [1]. This assessment step ensures that probabilistic safety assessments (PSAs), failure modes and effects analyses (FMEAs), and reliability principles become suitable and effective tools for evaluating the entire lifecycle process of nuclear fuel.

This process-oriented approach is used as a basis for combining nuclear safety code requirements and major industrial lifecycle business processes into one QA system.

2. Typical regulatory standard and related QA standard configuration

For the purpose of structural generalization most of national nuclear safety regulatory and related quality standards could be combined into three groups:

Group I standards originally related to military and full-scale nuclear fuel cycle applications. The standards are deterministic, product-oriented, with clearly identified key dimension and special processes key parameters (e.g., fuel cycle, and military and isotope products). Related classical statistics are applicable to serve or control production processes.

Group II standards originally served only NPGS applications. This group related regulatory standards are operationally safety oriented. Technological processes are organized into technological, support, and safety-related systems and characterized by key parameters: technological key parameters, and safety key parameters (or operational limits for the technological parameters). Process application of the standards is naturally probabilistic (e.g., PSA). Non-classical Bayesian statistics are suitable for operational application of these standards. These basic product realization processes are called industrial, parametric, or horizontal business processes in distinction to vertical or functional processes which do not serve product parameters directly, but serve and control horizontal industrial processes—their purpose is to perform a particular control or service function

Group III standards were originally oriented towards nuclear power applications, which lately have involved in-production applications (isotopes) mostly at the R&D stage of generic applications. These standards combine group I and II features.

For further generalization, it is understood that most of the provisions of national standards are incorporated in related IAEA standards. IAEA standards are considered to be the basic nuclear safety and regulatory scheme for the purpose of this paper.

For the purpose of this paper, the third group of safety and regulatory standards is interesting, as a combination of two different structural approaches. This structural combination includes the original design and R&D as one of the facility lifecycle stages. The R&D/design application is unique from the point of view of the variety of methods, products, and processes that are involved. At the pre-design stage R&D is used to form the future design concept, which makes this R&D stage become a part of the financial business-decision-making process and naturally links financial risk assessment statistical tools with ones used in QA and safety-standard processes. The implementation of statistical methods and tools is a subject of Sections 3 and 4 of this paper. IAEA standards for R&D (group III regulations), particularly irradiation and R&D experimental fuel for research reactors (RRs) were chosen to be applied, to test the suitability of the IAEA standards configuration to serve regulatory and industrial business processes.

The fact that the IAEA QA standard does not use unique QA terminology (as stated in the glossary note of the standard) reflects the situation that this standard is specifically functional (i.e., hierarchical, vertical) and serves as a supplement to the QA standard chosen for major production business processes (that are horizontal, parametrical). This standard consist of the following codes:

Safety Code No. 35-S1 is not directly used in the paper.

Safety Code No. 35-S2 [2] structurally covers all functional areas associated with safe operations of RRs. Section 12 of this code provides provisions for RR utilization based on the classification of RRs by function.

Quality Assurance Code 50-C-Q [3] consists of basic requirements and specific information divided into three sections. These sections define functional requirements for management, performance, and assessment.

Quality Assurance Guides 50-SG-Q1– Q7 cover basic functional requirements of the code.

Quality Assurance Guides 50-SG-Q8– Q14 are related to the implementation of QA Code 50-C-Q at different lifecycle stages of nuclear facilities. In particular, R&D QA Guide 50-SG-Q8 refers to RR Safety Codes No. 35-S1 and -S2. The functional classification of RRs provided in Section 12 of Safety Code No. 35-S1 could be utilized in QA Guide 50-SG-Q8 to link the functional approach of this standard with R&D business processes. In actual fact, this guide does not distinctly identify and separate two sets of QA functional requirements: ones related to the safety of R&D (RR) performance; and ones related to the results of this performance. In terms of the reactor core, this means that this guide mixes requirements for reactor irradiation fuel and R&D experimental fuel, which belong to different processes. Some attempt is made to provide an example of an R&D process-based approach in the annex of this guide.

3. Business standard configuration – process-based approach

ISO 9000:2000 Standard [4]. The first six sections of the standard describe the fundamental principles and methods of the quality management system: the process approach; and the factual approach make serious differences in applications of IAEA and ISO QA standards. The factual approach means that the decision-making process is based on measurable criteria.

These two principles combined satisfy qualitative and quantitative requirements for implementing reliability analyses of QA system processes. The reliability analysis methodology could be similar to methods described in the IEEE Guide for General Principles of Reliability Analysis of NPGS Safety Systems [5].

As far as IAEA standards are functionally and hierarchically (or vertically) oriented, the standards should be tested by implementing these functional requirements in parametric industrial business (or horizontally oriented) processes. A regulatory process that describes the control of the nonconformity feature of the ISO standard as a part of a continuous improvement process is shown graphically in Fig. 1.

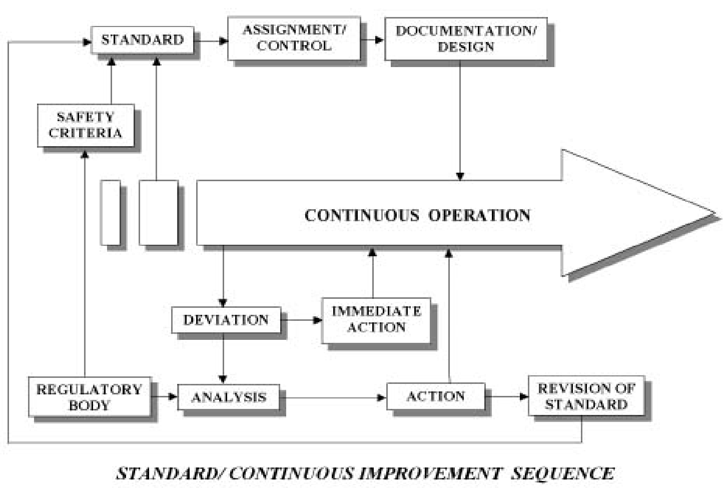


Fig. 1. Regulatory/operation process related to ISO 9001:00 Control of nonconformity.

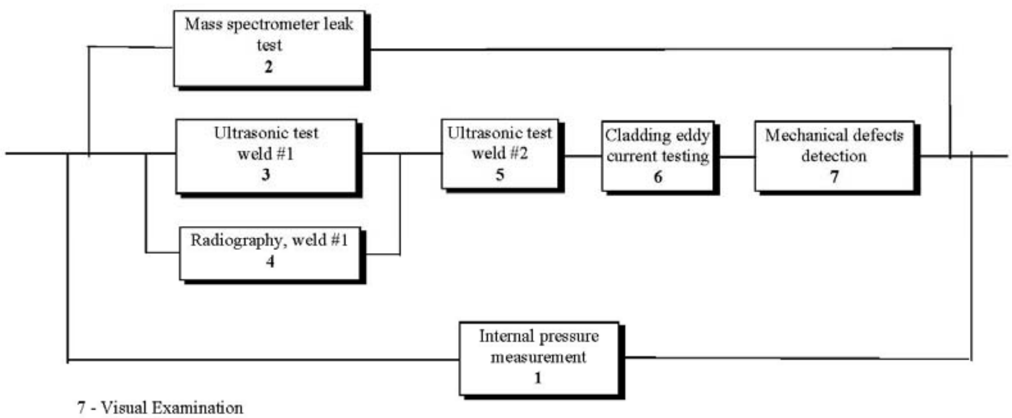
Applying this kind of test diagram to different types of R&D processes/facilities, the following additional comments on the complexity of implementation of IAEA and ISO standards could be made:

- Concept of systemic continuous improvement has not been a basis for development of this IAEA operation-oriented standard. Otherwise, the logical combination of IAEA and ISO standards with provisions for statistical performance/process evaluation would be realized.

- IAEA made an attempt to compare ISO 9000:2000 and IAEA QA standards in Safety Report No. 22 [6]. Unfortunately, the process-based approach with measurable performance criteria was not discussed in this document. As a result, ISO 9000:2000 was recommended only for supplier QA programs.

4. Approach to R&D business and regulatory standards alignment

One of the practical features of ISO 9000:2000-oriented nuclear business management is the mapping of processes with built-in regulatory requirements. This process mapping creates the basis for process parametric reliability evaluation—final mapping against major process parameters would allow the (QA) system performance to be measured in terms of process reliability. The reliability of process control and process result data is the most important criterion of the QA-process-based approach.



Availability factor of the system $p_s=[1-(1-p_1)(1-p_2)(1-p_3)(1-p_4)]\cdot[1-(1-p_1)(1-p_2)(1-p_5)]\cdot[1-(1-p_1)(1-p_2)(1-p_6)]\cdot[1-(1-p_1)(1-p_2)(1-p_7)]$

Fig. 2. Reliability diagram of mechanical integrity and leak testing of a fuel rod.

Therefore, the basis for any evaluation of processes is a reliable data management tool. A quality plan (QP), as a data-obtaining tool of the QA program, is suited to the analysis of the QA program. From the viewpoint of reliability theory [7], the QP can be treated as a system; thus, QP (QC) procedures should be evaluated as this system's elements. Among the important measures of reliability is the availability factor—the probability of a unit (or system element) to operate satisfactorily at present instants of time. This type of QP-based system reliability diagram of mechanical integrity and leak testing for nuclear reactor fuel rod fabrication is depicted in Fig. 2. The diagram includes only acceptance inspection and test elements. In this particular case the availability of this information (data-obtaining) system is expressed as the probability of detecting specified defects or out-of-tolerance parameters. In other words, the probability of providing reliable QC data is calculated in terms of the availability factor.

For the monotonic system presented, the availability factor of this system [8] is

$$ps=[1-(1-p1)(1-p2)(1-p3)(1-p4)]\ [1-(1-p1)(1-p2)(1-p5)]\ [1-(1-p1)(1-p2)(1-p6)]\ [1-(1-p1)(1-p2)(1-p7)],$$

where p1, p2, p3, … are availability factors for the system elements marked as 1, 2, 3,… in Fig. 2. In other words, p1, p2, p3, … are availability factors for the data provided by these acceptance tests.

Thus, using this equation, it is possible to make rough estimates of the availability factor ps—it is 0.69 for one of the real fuel rod manufacturing system.

For the purpose of continuous system improvement, measurements of the importance of system components should be applied. A mathematical theory of component importance is described in relative maintenance and reliability literature [8]. The practical application of importance principles meets the continuous improvement requirements of ISO 9000:2000. The continuous improvement approach was graded in terms of component importance for mechanical integrity and leak test data reliability (see Fig. 2). This means that improvement efforts were focused on more important components, and improvements were measured in terms of a component availability index. Finally, the availability index of the whole system was improved to 0.85, which is close to data availability indexes for RPBCs.

A system reliability diagram could be developed for evaluating the data reliability of nuclear fuel rod operational performance as a part of an R&D process. In this operational performance diagram, the whole fabrication data reliability diagram (see Fig. 2) will be presented by one element, with availability index equal to 0.85. Consequently, the availability factor for fuel performance data is an element of the data reliability system for fuel decay-product release. The level of decay-product release is the regulatory limit of reactor operational performance. The related grading approach of regulatory principles is also based on the safety importance of systems and components. This means that the same approach and reliability mathematical model (including importance theory) could be used for other regulatory licensed facility operational processes/key parameters, to determine in an integrated and systematic fashion whether the licensee is satisfactorily complying with the QA program requirements imposed by the regulations, and whether the licensee's QA program is effective in providing adequate confidence in the observance of safety criteria.

Similar QA plans and reliability diagrams could be used for the data availability factor for RR irradiation and experimental fuel rod manufacturing tests. The modular decomposition [8] of such systems for experimental fuel applications will provide a model for the reliability evaluation of the following R&D, design, and manufacturing data elements:

- The reliability of initial data, and the accuracy and reliability of approximations used for R&D computer codes.
- The reliability of R&D fuel manufacturing specifications.
- The reliability and accuracy of NPGS fuel specifications, including the elimination of so-called "vague" or hidden specification parameters.
- The reliability of operational data related to root-cause analysis of fuel rod leaking statistics [9].

Along with providing reliability diagrams, FMEAs and fault tree analyses are used at in first stages of complex system analysis.

5. Conclusions

Although the application of QA standards (code and guides) differs a lot for different configurations of facilities and lifecycle stages, especially for R&D the proposed method is a suitable way of QA evaluation in the nuclear industry, because

- this method uses the same methodology and theory as PSA, which is proven by practice.
- the method could be limited to different levels of complication, beginning from systemic expert evaluation up to the application of a statistical Bayesian approach for the design of experiments.
- at any of these levels the evaluation is based on measurable criteria without the loss of evaluation system integrity.
- a tool such as a fault tree analysis used in a PSA is similar to a decision-flow diagram that forms the basis for (financial) business decision analysis theory—as an example, please see Howard Raiffa, Decision Analysis [10].
- the method naturally includes FMEA and reliability theory, as

6. References

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